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ADAPTATIONS TO ADVERSITY AGRICULTURE, CLIMATE AND THE GREAT PLAINS OF NORTH AMERICA

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The climate of the Great Plains of the United States and Canada has presented a challenge to agrarians throughout the centuries. In this paper I discuss some of the major climatological hazards to agriculture in the plains and some of the technological defenses that North Americans have so far used to adapt to adverse weather and climate. I conclude with a consideration of the implications for Great Plains agriculture of a likely man-induced (or anthropogenic) climatic change following the expected further increase of carbon dioxide in the atmosphere. For the purposes of this paper, I have defined agricultural drought as a climatic excursion involving a shortage of precipitation sufficient adversely to affect crop production or range production (Rosenberg 1980). Agricultural land can only be productive when there is a balance between moisture supplied to the land by precipitation or irrigation and that withdrawn by evaporation from the soil or transpiration through plants (together called evapotranspiration). Drought, of course, affects not only water supply, but because of drier air and reduced cloudiness increases the rate of water consumption, while water is yet available to be withdrawn.

Drought has always been the most severe climatic constraint on plains agriculture. Tree rings and human accounts record a persistent pattern of droughts as far back as we are able to trace history. Some were severe, some less so, but all affected the crops and people of the plains. Early explorers of the Great Plains for the fledgling United States reported that the area was a near desert, unsuitable for agriculture. Some writers have suggested that the explorers may have seen the area during a drought. Historian William Goetzmann, however, considers that whether they did or not, given the available technology, the early explorers were correct in their pessimistic view of what they saw (Goetzmann 1966). Fur traders and settlers reported droughts in the Canadian prairies as well. During the settlement period in the 1870s, when rainfall was ample, hopeful scientists hypothesized that "rainfall follows the plow" (Aughey 1880).

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Although the return of droughts soon punctured this hypothesis, it is echoed today perhaps with more validity as some speculate that irrigation is moderating the climate and increasing precipitation in the Great Plains (Schickedanz 1976). Mathematical modeling of the influence of vegetation and other surface features provides a possible explanation for such a phenomenon (Anthes 1984).

Drought, however, seems likely to be a recurrent factor in the Great Plains climate for as long as we can see into the future. Nor is drought the only hazard crops face. Corn, sorghum, winter and spring wheat, and soybeans all run the gauntlet of climatic stress, as must all crops grown in the plains. Let us look, for example, at what may face the winter wheat crop each year. Shortage of soil moisture at seeding time may cause poor germination and sparse stands; heavy rains at seeding time may compact the surface, preventing seedlings from emerging; too little rain after seeding may retard growth and root establishment. Ice storms may smother young shoots; light snow may not provide a sufficient blanket against the winter's cold. A cool wet spring may promote the development of fungal diseases; a hot dry spring may stunt the plants; an early spring may break plant dormancy, causing rapid growth and flowering in time to be nipped by late frosts. Even when the weather is absolutely benign from seeding on, wind and hail can destroy a fine wheat crop days before the harvest should begin.

On the other hand, the plains climate presents advantages to the farmer. At any given latitude the intensity of solar radiation increases almost linearly from the Mississippi River to the Rockies with increasing altitude and decreasing cloudiness. As one moves westward, the air is drier and, except near local sources of pollution, less turbid. Mechanized harvesting equipment is more efficient in the dry western autumns than in the humid east. The strong cleansing winds of the plains sweep pollutants and transpired water vapor away from plants and resupply the carbon dioxide necessary for active photosynthesis.

Although drought is only one of the climatic hazards that limit crop production in the Great Plains, it is probably the most serious. The effects of drought can be understood more clearly if we focus on, for example, wheat production. From 1926 to 1972 wheat yields steadily increased, except during the drought years of the 1930s and 1950s, when the percentage of acres planted but left in the field as not worth harvesting was also greatest (fig. 1). The yield trend leveled off after the early 1970s. We also observe a period of sharply lower yields during the mid-1970s (fig. 2). The 1974 crop was seeded into moist soil,

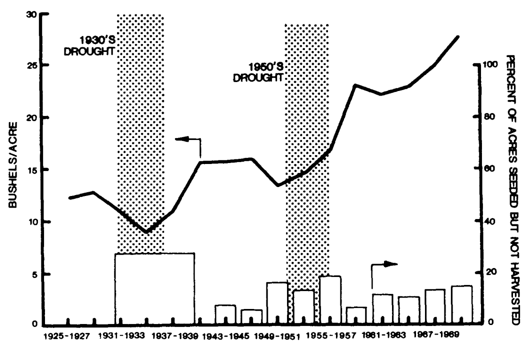

FIG. 1. *Wheat yields in the Great Plains region (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Montana, and Colorado) 1925-1969.* Source: National Academy of Sciences 1976.

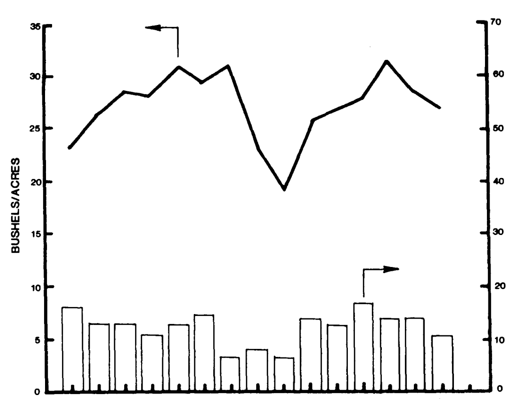

FIG. 2. *Wheat yields in the Great Plains region (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Montana, and Colorado) 1967-1981.* Source: *Agricultural Statistics, 1967-81.* GPO, Washington, D.C.

but a very hot, dry early summer, followed in some places by hail, lowered yields sharply. The 1975 crop went into a dry seedbed, and fair spring rains could not redeem spotty stands that produced the lowest yields of the decade. The 1976 crop also went into a dry seedbed and suffered from poor snow cover. Spring rains were followed by a hot, dry summer. Although yields have been rebounding since then, this three-year period shows that, despite improved technology, even a relatively mild drought can still severely reduce wheat production in the Great Plains.

In the past few years another complicating consideration has arisen—the possibility that humans will cause changes in the composition of the atmosphere leading to change in our climate. The increasing concentration of carbon dioxide and other radiatively active gases in the earth's atmosphere must produce a "greenhouse effect" that warms the lower layers of the atmosphere. This warming will alter the global hydrological cycle. Some global climatic models predict significant change in precipitation and evaporation in regions such as the Great Plains.

TECHNOLOGY VERSUS DROUGHT ON THE GREAT PLAINS

In March 1979, a group of climatologists, agronomists, farmers, and other knowledgeable persons examined the technological, political, economic, and social strategies that might be used to ameliorate the effects of future droughts on the Great Plains (Rosenberg 1980). The group that dealt with technology developed a comprehensive list of strategies for minimizing the impact of drought and improving the agricultural stability of the region. The following technological procedures are intended either to increase water supply or to decrease water demand.

Irrigation. For some farmers irrigation provides the major defense against drought. By 1929 some seven million acres of land in the Great Plains states were irrigated, a figure that remained relatively constant until 1940, then climbed steadily until it evened out at just over thirty million acres in 1975. Irrigation has made possible a significant increase in the production of grains, especially corn, in large portions of the plains. Corn is now a major

TABLE 1

TOTAL IRRIGATED ACREAGE, ACREAGE BY IRRIGATION METHOD AND ACREAGE OF MAJOR CROPS IRRIGATED IN GREAT PLAINS STATES IN 1983 WITH COMPARATIVE DATA FOR OTHER GRAIN PRODUCING STATES (ALL FIGURES x1000)

State	Total Acreage Irrigated	Gravity Systems	Center Pivot	Corn	Sorghum	Wheat	Other Small Grains	Soybeans
Colorado	2,790	2,130	600	700	110	170	210	9
Kansas	3,489	2,199	1,203	1,080	726	602	———	220
Montana	3,170	2,904	59	75	———	125	215	———
Nebraska	8,088	4,520	2,888	4,700	600	400	6	890
New Mexico	1,400	1,249	145	120	136	185	44	———
North Dakota	211	45	151	99	———	———	15	< 1,000
Oklahoma	742	342	219	36	167	216	6	15
South Dakota	457	60	314	221	10	16	11	24
Texas	7,800	6,100	1,000	750	850	1,400	———	200
Wyoming		1,558	115	100	———	20	175	———
TOTAL	29,917	21,107	6,694	7,881	2,599	3,134	682	1,358
Illinois	151	< 1,000	110	95	———	2	———	39
Indiana	116	6	82	83	< 1,000	———	———	12
Iowa	283	22	202	188	1	———	———	39

SOURCE: Irrigation survey '83, in *Irrigation Journal* 34, (March-April 1984).

crop in central and western Nebraska and its culture has been extended to central and western Kansas and eastern Colorado.

Tables 1 and 2 show the extent and type of irrigation in the plains states and illustrate just how important irrigation is to grain production in the region. At present, irrigation functions as the ultimate drought-proofing technique, but it is not at all clear that the current irrigation base is sustainable. Not only is water itself a finite resource, but energy costs and market considerations may limit its use. Some currently irrigated land will ultimately revert to dry land agriculture. More efficient use of water in irrigation is certainly possible with the introduction of scientific irrigation scheduling methods, improvements in equipment, and the limitation of irrigation to critical periods of crop growth only. However, while technical improvements in irrigation may prolong its use in some areas, some lands in the Great Plains will necessarily revert to dryland farming. Evidence from Nebraska shows that some farmers have already begun to abandon or relocate irrigation systems. In 1983 24,420 center pivot systems remained active out of 25,798 total pivots that had been observed at one time or another in the state. (This data was provided by Marvin Carlson, Conservation and Survey Division, University of Nebraska–Lincoln. A map of working center pivot irrigation systems is published annually by the Conservation and Survey Division.) Although we should be prepared for the abandonment or reconversion to dryland agriculture of lands now under irrigation, it is important to emphasize that the efficiency of irrigation *can* be improved and the useful life of

TABLE 2

TOTAL PRODUCTION OF GRAIN CROPS (IN METRIC TONS) AND PERCENT OF TOTAL UNDER IRRIGATION IN THE GREAT PLAINS STATES, 1981-1982

	Corn		Sorghum		Soybeans		Wheat	
State	Total Production	% Under Irrigation	Total Production	% Under Irrigation	Total Production	% Under Irrigation	Total Production	% Under Irrigaton
Colorado (1982)	1,503,512	99	164,239	57	——	——	1,191,805	13
Kansas (1982)	1,909,796	78	2,640,283	37	640,957	——	6,292,440	9
Montana (1982)	19,068	100	——	——	——	——	2,500,087	3
Nebraska (1981)	10,932,774	81	2,094,938	14	1,126,101	21	1,446,444	4
New Mexico (1982)	134,838	——	185,214	64	——	——	180,465	51
N. Dakota (1982)	481,603	——	——	——	98,677	——	4,505,292	> 1
Oklahoma (1981)	52,437	——	280,300	31	88,258	——	2,353,536	4
Texas (1982)	1,630,314	73	2,172,989	29	325,790	——	1,961,280	33
Wyoming (1980)	48,882	99	——	——	——	——	115,933	4

—— equals no data available

SOURCES: Colorado Agricultural Statistics (1982), Colorado Dept. of Agriculture, Denver; 65th Annual Report and Farm Facts (1981), Kansas State Board of Agriculture, Topeka; Kansas County Data (1982), Kansas Crop and Livestock Reporting Service, Kansas State Board of Agriculture, Topeka; Montana Agricultural Statistics (1982), Montana Crop and Livestock Reporting Service, Helena; Nebraska Agricultural Statistics, 1981, Nebraska Crop and Livestock Reporting Service, Lincoln; New Mexico Agricultural Statistics (1982), New Mexico Crop and Livestock Reporting Service, Las Cruces; North Dakota Agricultural Statistics (1982), North Dakota Crop and Livestock Reporting Service, Fargo; Oklahoma Agricultural Statistics (1981), Oklahoma State Board of Agriculture, Oklahoma City; 1982 Texas Field Crop Statistics, Texas Crop and Livestock Reporting Service, Austin; 1982 Texas Small Grains Statistics, Texas Crop and Livestock Reporting Service, Austin; Wyoming Agricultural Statistics 1981, Wyoming Crop and Livestock Reporting Service, Cheyenne.

aquifers extended. I discuss some such irrigation strategies in the following section.

Other techniques for increasing supply: water harvesting. "Water harvesting" is an ancient practice in arid lands. It is simply the impoundment of runoff water in small depressions in fields or floodplains. Because such microcatchments can cause severe flooding of planted areas when precipitation is heavy, this technique has been used thus far in this region only for a few high-value crops grown in the southern plains, but water harvesting could be used more heavily in areas with low rainfall.

Conservation tillage. No-till, ridge-till, strip-till, mulch-till, and other reduced tillage practices are all ways of limiting either the number of tillage operations or the percentage of the soil surface to be tilled in producing a crop. The technique is particularly useful where chemical herbicides are effective in weed control. Conservation tillage reduces soil erosion by wind and water and increases soil moisture availability in times of drought (Greb 1979; Wittmuss and Yazar 1977). Conservation tillage is gaining rapidly in popularity, despite some persistent problems such as uneven germination, low spring soil temperatures, possible overwintering of plant diseases and insect pests, and the possible buildup of environmentally undesirable chemical herbicides. Nonetheless, the advantages of conservation tillage for improving soil moisture, protecting topsoil, and reducing energy and labor costs for cultivation indicate that such techniques will continue to attract new practitioners.

Snow management. From the Canadian prairie provinces as far south as Kansas, a significant percentage of the annual precipitation falls as snow, but snow is likely either to blow away or to melt and run off over frozen ground in the spring. If the wind speed near the surface of the ground can be reduced, snow is deposited more evenly and is more likely to melt uniformly, replenishing soil moisture. Tree windbreaks, sown windbreaks, constructed barriers such as snow fences, annual or perennial crops like grasses, or standing stubble of a previous crop—all serve to hold snow. Barriers such as tree windbreaks cause some problems, discussed below in the section on windbreaks. Nonetheless, wind barriers for snow management can be crucial, particularly at the arid edges of grain-growing regions, where even small increments of water produce significant increase in yields (Aase and Siddoway 1976; Pelton and Earl 1962).

Improved cultural practices. Conservation tillage is only one of the modern improvements in cropping practices that maximize crop production while conserving soil and water. Other innovations include fertilization, strip-cropping, crop selection and rotation, and skip-row planting. Areas that merit further research include finding better ways to supply nitrogen to dryland crops without either injuring the plant or prolonging the vegetative period. We also need to know more about plant and row spacing in a variety of climatic conditions. High plant populations are best when precipitation and soil moisture supplies and nitrates are adequate; but in times of moisture stress, particularly, yields can be reduced sharply as the plants compete with each other for limited moisture. Systems of planting that are attuned to the expected weather conditions would be best—but since weather forecasting is yet far from perfect a reasonable alternative is to work with planting systems and populations that can be reduced if drought conditions develop.

Soil evaporation reduction. Systems of reduced tillage that maintain crop residues, promote the formation of clods, increase soil absorption, reduce evaporation and erosion, and control weeds increase stored soil moisture. Crop residues and other mulches reduce evaporation by creating a vapor barrier, lowering soil temperature, and diminishing wind speed at the soil surface. Plowing weeds under exposes moist soil to the air, so chemical weed control may be preferred to save water.

Research to integrate chemical and mechanical weed control is needed to adapt fallowing systems to areas of varying rainfall, soil texture, organic matter content, and pH.

Where irrigation water is scarce, it can be used more efficiently if it is only applied at critical stages of crop growth like tasseling and silking, head emergence, or pod and bean development. Such strategic irrigation of sugar beets in Texas has saved considerable water with little loss of yield (Winter 1981). Similar research has pointed to the same results with sorghum and wheat (Stewart and Musick 1982). Strategies for limited irrigation, carefully synchronized with actual rainfall, need to be developed for a variety of cropping systems under the full range of expected climatic conditions, including drought.

Decreasing demand: alternative crops. One way to solve a problem may be to avoid it. New crops that require less water than those currently grown may help farmers survive droughts. Pearl millet, amaranth, and guar are food crops suitable for dryland farming or limited irrigation. Forage sorghum and guayule, a source of latex, are possible specialty crops, while kochia and fourwing saltbush are potential additions to our ranges. Of course, breeding, cropping-system development, and marketing research are needed before any new crop can be introduced successfully.

Windbreaks and shelterbelts. Modifications of the climate of small areas such as single fields can produce significant decreases in a crop's demand for water. Among the most successful of such modifers are windbreaks and shelterbelts to temper the cold winds of spring and fall that would otherwise break and tear plants and the hot dry summer winds that not only cause mechanical damage to plants but also dessicate them. Wind erosion on unprotected land can cause a permanent decline in productivity. Young tender vegetation may be destroyed by the "sand blasting" effect of wind-carried soil particles (Sturrock 1975; Grace 1977). Properly designed windbreaks shelter crops, distribute snow over the fields, and essentially moderate the microclimate during the growing season. In the lee of tree windbreaks and other barriers the air is slightly warmer by day and slightly cooler by night, and the absolute humidity is consistently greater. Evaporative demand is reduced and plants are exposed to less moisture stress. Thus they are less likely to wilt, close up their stomates, and cease photosynthesis. Evidence from around the world shows that, in fact, sheltered crops produce greater yields (Van Eimern et al. 1964; Marshall 1967; Rosenberg 1979; Grace 1977).

Shelter is normally beneficial to plant growth, most directly because it enables plants to conserve moisture for later use. Even when plant water needs are supplied by irrigation, however, shelter reduces turbulent exchange, increases the amplitude of the temperature wave, and humidifies the air without reducing the concentration of carbon dioxide. Shelter does not consistently reduce evapotranspiration because unsheltered plants can protect themselves by closing their stomates, but even if the sheltered plants sometimes transpire more water they continue photosynthesis more efficiently than unsheltered plants.

Despite the proven utility of windbreaks, many that were planted in the Great Plains during and after the drought of the 1930s are now being removed. The older windbreaks get in the way of the large center-pivot sprinkling systems that have revolutionized irrigation in the plains. In other cases the shelterbelts have become overgrown and inefficient as windbreaks. When land values increased, farmers begrudged the space occupied by windbreaks. Whether falling land values will result in the sparing of trees remains to be seen. Farmers urgently need windbreak designs compatible with current and foreseeable cultivation patterns in the windswept plains. Tall annual crops such as corn, sorghum, or ryegrass can be planted in fields of shorter crops to provide shelter or to augment shelter provided by widely spaced tree windbreaks (Rosenberg 1977). This idea is not new, but much research is needed to develop appropriate management systems.

Reflectants. Scientists have suggested that by increasing plant albedo (reflectivity) the net energy load placed upon the plant by the sun could be reduced, leading to diminished evapotranspiration (Seginer 1969; Aboukhaled et al. 1970). Several experiments that involved coating plants with light-colored substances such as kaolinite and Celite have shown this to be the case. Whatever the weather conditions, higher reflectance leads to reduced evapotranspiration. In relative terms, reflectants are best when solar radiation is the only source of energy available to evaporate water. On many days during the crop-growing season in the Great Plains an additional source of energy is imposed on the plants. This energy is borne by hot dry winds originating in drier regions to the south and west. Since reflectants have no influence on the delivery of this "advected sensible heat," their relative effectiveness on these days is less, yet they do continue to decrease evaporation somewhat. Although we do not yet fully understand why reflectants decrease water use, scientists believe that reduced net radiation, increased stomatal resistance, a reduction in the plant's ability to cool itself by emitting long wave radiation, and other factors are involved.

Even though reflectants reduce evapotranspiration, water use efficiency can increase only if photosynthesis is not also reduced. When my colleagues and I experimented with soybeans at the University of Nebraska's Agricultural Research and Technology Center near Mead, we did not expect that "reflectorizing" the plants would cause photosynthesis to decrease because that crop receives more light during most of the day than it can normally use. (It is light-saturated.) We found, in fact, that coating the plants with reflectants did not reduce photosynthesis and yield at all since light was reflected into interior leaves that were normally shaded and light-unsaturated. Even when grain sorghum, a crop not normally light-saturated, was reflectorized, grain yield increased although photosynthesis was actually reduced. The researchers hypothesized that the reflectants speeded up the plant life cycle, hastening the formation of seedheads and the diversion of plant energy and nutrients to the developing grain (Moreshet et al. 1977).

Natural reflectants: plant architecture. Powdering plants with clay dust and other such materials is not likely to prove practical on a large scale, though it might prove useful in an emergency water shortage if labor is plentiful and inexpensive. Breeding plants for natural reflectance seems to be a more promising approach. Albedo varies from species to species and within species according to the age of the leaf, the concentration of chlorophyll, and the presence of wax on the leaf surface. Several researchers have found also that plants with hairy leaves are more reflectant, resulting in certain advantages to the plant (Wooley 1964; Ghorashy et al. 1971; Gausman and Cardenas 1973; Ehleringer and Bjorkman 1978). My colleagues and I have conducted several experiments with paired isogenic cultivars of soybeans that differed only in the density of leaf hairs. The densely hairy isogene had four times as many hairs per unit area as the normal isogene (Baldocchi et al. 1982, 1983a, b). Although photosynthesis and yield over the season were the same for both types of soybeans, evapotranspiration was approximately 7 percent less in the hairy (pubescent) plants. On hot windy days the ratio of carbon dioxide captured to water vapor transpired was 30 percent more favorable for the hairy-leafed beans. The hairy leaves also reflected more light into the shaded interior of the plant canopy.

This research on reflectance in hairy soybeans has practical implications for strengthening and stabilizing agriculture on the Great Plains. Soybeans are currently grown in concentration about as far west as Lincoln, Nebraska. Corn, especially irrigated corn, predominates west of there. While corn is very vulnerable to hot dry weather, particularly during the reproductive stage, soybeans are less so. The introduction of hairy soybean varieties into the drier western areas can provide a degree of "drought-proofing" to that region; such varieties are now being developed for that purpose.

Irrigation scheduling. Although I have discussed irrigation as the major drought-proofing strategy on the Great Plains, I want here to discuss irrigation scheduling, a complex technique that can substantially reduce demand for irrigation water. Precise measurements of the water content in the soil and of cumulative daily evapotranspiration, plus accurate weather forecasts, are needed for efficient irrigation scheduling. National Weather Service stations are ordinarily located at airports or other places unlike agricultural fields and are too few to be of use for the precise measurements needed, so we in Nebraska have developed the Automated Weather Data Network (AWDN). At the end of 1985 about twenty-nine weather stations throughout the state were linked in this network. Each station consists of weather instruments mounted on a three-meter tower. The instruments measure wind speed and direction, air temperature and humidity, solar radiation, soil temperature, and precipitation. A microprocessor monitors each of the sensors and calculates and stores hourly averages or totals. Every morning, at about 3 A.M., a computer at the Center for Agricultural Meteorology and Climatology in Lincoln calls the stations, in order, using voice-quality telephone lines. The microprocessor transmits the data stored for the previous twenty-four-hour period. The computer can also call the weather stations at any time. After calling each weather station the computer checks the data and flags questionable data to be checked by a specialist. The computer then sorts the data and finally transmits it to the mainframe computer, which stores all the data accumulated by the network since its inception. We expect that the Nebraska network will grow to between thirty and forty stations. Twenty more stations in Kansas, South Dakota, Wyoming, and Colorado are also linked to the network. Since the collecting computer can handle one hundred or more stations, more private or non-Nebraska stations can be accommodated if demand for them arises.

The mainframe computer, referred to above, operates an agricultural management network known as AGNET through which the AWDN data may be retrieved by telephone or automatically called into use for specific programs. Farm managers and consulting services use the AWDN data for scheduling irrigation, one consultant managing more than 100,000 acres with the data provided by this system. Irrigators must know soil type and characteristics of the irrigation system. Information on soil moisture content, water requirement by crop, cumulative and probable evapotranspiration, and the likelihood of rain can all be obtained with assistance of the AGNET system. Since center pivot systems require two to four days to rotate once around a field, forecasts must be continually updated to provide adequate lead time. The data collection of the AWDN and the distribution network of AGNET make the combined system an efficient management tool. Although primary emphasis in the development of AWDN was to support and improve irrigation scheduling, the system is also being used for drying grain, designing animal rations, estimating crop development and livestock weight gains, and predicting crop yields. The network and its operation are described in detail in Hubbard et al. 1983.

CLIMATE CHANGE

Climate is always changing. Anyone who wants to take a long view must remember that the tilt and orbit of the earth change in predictable cycles of 26,000, 41,000 and 97,000 years. When solar activity has been less than it is now, the climate has been colder. Since we have no control over the activity of the sun (probably the major extraterrestrial force of climate change) nor even over the activity of volcanoes (probably the major terrestrial force in climate change), I have

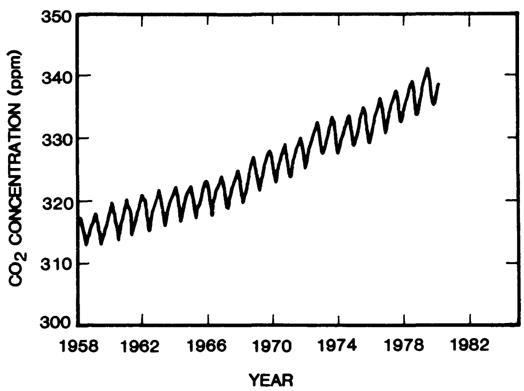

FIG. 3. *Atmospheric concentration of carbon dioxide at Mauna Loa Observatory, Hawaii, 1958-1980.*

confined my remarks in this section to the types of climate change that human beings may be causing and thus can to some extent control. We change climate by three mechanisms: by changing land use and altering the reflectivity and other properties of the surface, by aerosol loading of the atmosphere and reducing its transparency to radiation, and by altering the gaseous composition of the atmosphere. The latter of these mechanisms is especially relevant to assessing the vulnerability of the Great Plains to drought.

The increasing concentration of carbon dioxide in the atmosphere, caused primarily by the consumption of carbon-based fossil fuels, is one possible cause of climatic change. Mauna Loa, Hawaii, a mid-Pacific, high-altitude observatory, samples well-mixed air representing the mean condition of the atmosphere in the northern hemisphere. As fig. 3 shows, the concentration of carbon dioxide has been increasing constantly since the observations began in 1958. The rate of increase appears to be accelerating slightly, but in general the increase has been about 0.6–1.5 parts per million per year. The graph also shows an annual cycle, with the lowest concentration reached after the active photosynthesis of the northern hemisphere summer and the highest after winter, when the net transfer of carbon dioxide released by the respiration of living plants and animals and the decay of organic matter exceeds the capture of carbon dioxide by photosynthesis. The burning of fossil fuels releases carbon dioxide into the atmosphere throughout the year.

While carbon dioxide is virtually transparent to visible sunlight, it absorbs certain bands of the infrared spectrum. Thus carbon dioxide allows sunlight to reach the earth's surface but absorbs and back-radiates some of the thermal radiation emitted by earth. Atmospheric scientists believe that the increase in atmospheric carbon dioxide concentration may warm the lower layers of the atmosphere. A number of other gases also participate in causing this "greenhouse effect" (table 3). The potential impact of these gases on the temperature of the lower atmosphere is conservatively estimated in this table, since carbon dioxide alone, if its concentration doubles, has been estimated by some scientists to warm the atmosphere by somewhat more than the 2–3°C indicated.

Carbon dioxide and climate change. Green plants capture carbon dioxide from the air and convert it to simple sugars by photosynthesis. Almost all plants use water more efficiently when there is an increase in the carbon dioxide in the air around them. Some increase photosynthesis and some decrease transpiration. Thus, as the concentration of carbon dioxide in the atmosphere increases, we can expect more food and fiber to grow for each unit of water consumed by the plant. In fact, this may already be happening, since carbon dioxide concentrations (now approximately 345 parts per million) have increased by as much as 8 percent since 1958 and by perhaps one-third since 1860 (assuming a concentration then of about 260 parts per million). Of course these predictions of plant response are based on the assumption that the increase in the carbon dioxide concentration will not change the climate, but the possibility of major climatic changes resulting from the continued increase in carbon dioxide concentration has stimulated as much speculation and much more concern than the possibility of changes

TABLE 3
EXPECTED INCREASE IN THE CONCENTRATION OF RADIATIVELY ACTIVE GASES AND THEIR EXPECTED INFLUENCE ON MEAN ATMOSPHERIC TEMPERATURE

Gases	Expected increase (Multiples of Present)	Expected Temperature Rise (°C)
CO_2	2	2–3
CH_4	2–4	0.3–0.5
N_2O	1.5–2	0.4–0.7
CO*	1.5–2	0.6–0.9
$CFCL_3$, CF_2CL_2, etc.	5–10	0.0–0.1
CF_3, Br, C_2H_4Br, etc.	2–3	Negligible
CF_4	15	0.1
$CC1_4$	1.0–1.5	Negligible
CH_3C1	2	Negligible
		Range 3.4–5.2

*via influence on the ozone concentration.

in plant growth. Models developed by Syukuro Manabe and Richard Wetherald as well as those of other scientists predict a very significant increase in mean global surface temperature (Manabe and Wetherald 1980). Ad hoc committees of the National Academy of Sciences and the National Research Council (1979 and 1983) found no fundamental flaw or failure in these models, although other researchers consider that they may exaggerate the extent of temperature rise (Newell and Dopplick 1979; Idso 1980; Ellsaesser 1984).

Manabe and Wetherald used a global climatic model to test the effects of a doubling and quadrupling of the preindustrial carbon dioxide level. We may summarize their findings as follows: (1) The temperature in the surface layers of the atmosphere will increase by about 3°C in the zone of approximately 35°–50° north latitude. It will increase by a lesser amount to the south and by a greater amount to the north. (2) Precipitation will increase in the zone of approximately 12°–37° north latitude and decrease in the zone of 37°–50° north latitude. (3) Evaporation will increase relatively slightly at all latitudes. (4) There will be a net increase in available water (difference between precipitation and evaporation) between 12°–37° north latitude but a net decrease between 37°–50° north latitude. (5) Soil moisture supplies will change relatively little south of 37° north latitude but decrease significantly in the zone between approximately 37°–47° north latitude. The Manabe and Wetherald predictions of a decrease in the difference between precipitation and evaporation for latitudes 37°–47° north on their model continent have attracted considerable attention, since these latitudes approximately bound the major grain producing areas of the United States, the Soviet Union, and China.

Are Manabe and Wetherald's projections truly applicable to the real North American continent? If we search back in time four thousand to eight thousand years, we come to a period when the world was several degrees warmer than it is now, and the middle latitudes of North America seem to have been drier (Kellogg and Schware 1981). There are, however, reasons for caution before accepting Manabe and Wetherald's predictions at face value. Let us look at what happens to real crops on the contemporary plains. When alfalfa is well supplied with water, the crop behaves like a potential evaporator, extracting water from the soil and transporting it virtually without resistance through the plant and into the atmosphere. Net radiation on clear days at our experiment station near Mead, Nebraska, provides enough energy to evaporate about 6 to 7.5 millimeters of water per day in this environment, yet our precision measurements show that daily evaporation is often greatly in excess of this amount, at times in fact nearly twice what we might expect from the net radiation alone. Clearly some other source of energy plays a role in the evaporation process, and that other source is the heat brought into the region by hot dry winds from the south and southwest (Rosenberg 1969; Rosenberg and Verma 1978; Brakke et al. 1978). This phenomenon of "sensible heat advection" has also been observed in other portions of the western United States (Hanks et al. 1971; Wright and Jensen 1971). The greatest water use in alfalfa occurs during late spring and early summer—the period when windiness, rather than temperature, hits its peak. The evidence of the alfalfa observations suggests that general climatic changes may not change evapotranspiration in the grain belt so radically as the Manabe and Wetherald model predicts since both a general decrease in windiness and in the dryness of the southerly winds may also occur.

Regression analysis and climate change. The Manabe and Wetherald model predictions have alarmed some analysts who interpret them to mean an effective loss of much of the North American breadbasket as a grain-growing area. Those who have reviewed the model point out that an increase of 1°C in mean temperature translates roughly into an extension of the growing season by ten days. Less benign predictions suggest that summer temperatures may become too high for corn and soybeans, forcing these crops north to less fertile soils, and that climate may become more variable, leading to more frequent droughts and consequent reductions in corn yields. Relatively cool, wet conditions foster good corn yields, and U.S. corn production can change by 11 percent per degree of average maximum summer temperature change and by 1.5 percent for each 10 percent change in rainfall. Thus wetter areas like Indiana and Illinois might experience reduced yields as a result of temperature increase of 1° to 2°C, while drier states like Kansas and North Dakota might benefit from increased temperature and rainfall (Bach 1979).

Such predictions as those above are based on regression analysis, a statistical method for estimating crop yield as a function of the deviation from normal growing season or preseason climatic conditions. Such regression models are useful for estimating current season yields, but their application to climate change is more problematic. The regression models that reflect our knowledge of crop responses to climate are built on the assumption that crop varieties and production technologies will not change (or will change at a rate that has historical precedents) with the changing climate. Furthermore, the models do not consider the fact that the increased concentration of carbon dioxide in the atmosphere that will bring about the climate change is also likely to have direct and positive effects on the growth of wheat and corn by increasing photosynthesis in the former and reducing transpiration in the latter (Rosenberg 1981). Nor do regression models consider episodic events such as frosts, hailstorms, and high winds that can reduce yields (Rosenberg 1982b). Ralph Neild and his colleagues at the University of Nebraska have even suggested that the benefit to the northern edges of the grain belt of a longer growing season is not unambiguous. A warming trend might increase the incidence of freezing in early planted fields, leading ironically to effective climate cooling for the corn crop (Neild et al. 1979).

Deterministic and hybrid models. Since regression models were not developed for predicting crop yields under a wholly new climatic regime, it would not be surprising if they were to prove inadequate for the purpose. Deterministic models that consider the physics of energy and mass exchange between atmosphere and plant as well as plant physiological and phenological processes may be more useful because they need not rely on past data or means that obscure both the extremes and the episodic events that will strongly affect yields under changed conditions. Even more useful may be hybrid models combining deterministic and regression approaches. Paul E. Waggoner, using a regression approach modified by the results of more deterministic models, has concluded that a warmer, drier climate would decrease yields of wheat, corn, sorghum, and soybeans between 2 and 12 percent, or 5 percent overall once the enhancement of photosynthesis by increased carbon dioxide is factored in. Waggoner agrees, however, that the unknowns are so many and so important that he cannot be very confident in these predictions (Waggoner 1984).

Crop migration and climate change. Another way of predicting the effects of climate change is to examine historic patterns of the adaptation of crops to new climate conditions. Except for corn, all the major cash crops currently grown on the Great Plains are relatively recent migrants, and contemporary hybrid corn is a far cry from Native American maize. If we take the example of a single crop, hard red winter wheat, we can see that between 1920 and 1980 the area in which it was raised almost doubled (fig. 4, tables 4 and 5). While the crop retreated somewhat in the eastern part of its range because it was not economically competitive with other crops, such as corn and soybeans in Iowa, it advanced to the south and west. Irrigation, not widely available in 1920, enabled wheat to move south, while the movement north and northwest resulted both from the breeding of more cold-hardy winter wheats and the technical improvement of such dryland management practices as summer fallow and stubble mulching.

From Sidney, Nebraska, near the northwest corner of the hard red winter wheat belt in 1920, to Sidney, Montana, the crop had to adapt to an 88 mm (20 percent) decrease in mean annual precipitation, a 4.2°C decrease in mean annual temperature, and a ten-day decrease in frost-free season. Mocassin, Montana, and Tetonia, Idaho, offer a frost-free season twenty-five days shorter, and Tetonia also has a mean annual temperature 5.1° cooler. The move south from Denton to Kerrville, Texas, also involved significant climate differences. Kerrville receives 100 mm (12 percent) less mean annual precipitation than Denton, and although Kerrville's mean annual temperature is 1.6°C lower, its average frost-free season is 10 days longer (Rosenberg 1982b).

The migration of hard red winter wheat also involved changes in planting and ripening dates. North of Sidney, Nebraska, planting ranges a week to a week and a half earlier. Ripening dates are more variable than planting dates, varying from as early as 10 to 20 July in Sidney, Montana, to a mid-range of 25 July to 5 August in Sidney, Nebraska, to 1 to 10 August in Mocassin, Montana, and Tetonia, Idaho, to 1 to 15 August in Highmore, South Dakota. The movement south from Denton, Texas, has advanced both planting and ripening dates by about two to ten days. Although yields achieved either northwest or south of the 1920 winter wheat belt are usually lower, there are exceptions. Sidney, Montana, represents a low, with two tons per hectare, but Tetonia, Idaho, and Sidney, Nebraska, both produce three tons per hectare, as does Kerrville, Texas, lower than Denton's high of four tons per hectare (Rosenberg 1982a).

Conclusion

In this paper I have tried to put the drought vulnerability of the Great Plains into perspective. Drought is only one of the climatic adversities that face agriculturalists in the region, albeit the most serious. Irrigation is the most important of our technological defenses against drought, but it cannot be sustained

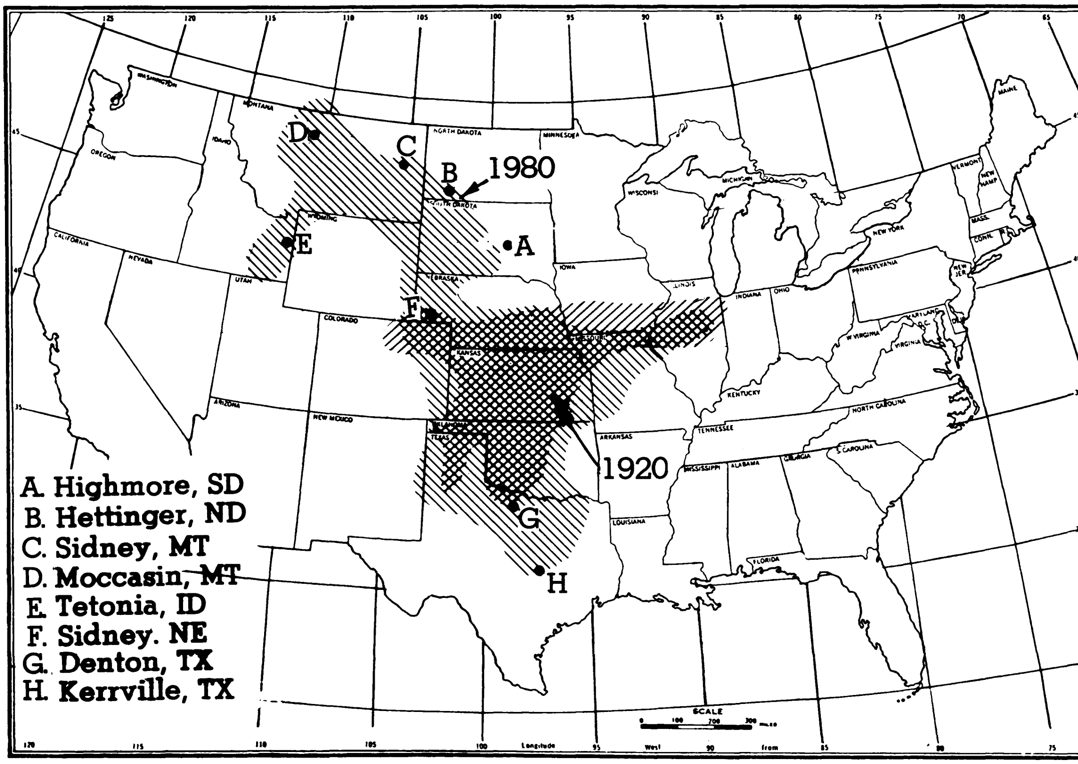

FIG. 4. *Extent of the hard red winter wheat zone in 1920 and 1980.* Source: Rosenberg 1982a.

indefinitely where it is based on the withdrawal of finite sources of groundwater. A promising development is irrigation scheduling based on fast and accurate measurements of soil and microclimatic conditions in our cropfields and efficient delivery of such information by interactive computer systems to potential users. Such systems can also make observation and surveillance of drought incidence and severity more objective and accurate than has previously been the case.

Other techniques for minimizing the effects of drought and managing semiarid lands are also available. Windbreaks both minimize wind erosion and stabilize crop yield, but many mature tree windbreaks are being removed as incompatible with modern farm machinery and irrigation systems. Annual windbreaks may help farmers, especially for distributing snow that can provide usable moisture for crops. Various methods of conservation tillage are gaining popularity, but their heavy reliance on chemical herbicides may cause new environmental problems. New drought-resistant crops promise some solutions, but they cannot quickly be brought into production. Conventional breeding techniques, or biotechnology to alter the physical architecture of crops, making them more drought resistant, may prove to be among the most successful and least environmentally disruptive of our technological options.

One of the most interesting questions about drought and the Great Plains is whether the "greenhouse effect" caused by the increasing concentration of carbon dioxide and other radiatively active gases in the atmosphere will increase the region's vulnerability to drought. I maintain that current fears the region will dry out are premature and unnecessarily gloomy. Agriculture has adjusted to changes even greater than those that are predicted to follow a doubling of atmospheric carbon dioxide. The violently fluctuating climate of the Great Plains will continue to challenge farmers, but neither the evidence of history nor the predictions of the most complicated computer models convince me that the region is likely to turn into a desert or, for that matter, an agricultural paradise.

REFERENCES

Aase, J. K. and F. H. Siddoway. 1976. Influence of tall wheatgrass wind barriers on soil drying. *Agronomy Journal* 68: 627–31.

Aboukhaled, A., R. M. Hagan and D. C. Davenport. 1970. Effect of kaolinite as an effective antitranspirant on leaf temperature, transpiration, photosynthesis and water use efficiency. *Water Resources Research* 6: 280–89.

TABLE 4

SELECTED EXPERIMENT STATIONS AND CLIMATIC CONDITIONS IN THE NORTH AMERICAN GREAT PLAINS WHERE HARD RED WINTER WHEAT IS GROWN

Location	Lat. (N)	Long. (W)	Elev. (m)	Frost free season (days)[a]	Mean ann. precip. (mm)	Mean ann. temp. (°C)	Annual temp. range, warmest–coldest month (°C)
A. Highmore, SD	44°31'	99°28'	576	145	477	7.0	32.7
B. Hettinger, ND[b]	45°59'	102°39'	817	130	408	5.0	31.8
C. Sidney, MT[c]	47°27'	104°21'	605	125	357	5.1	32.7
D. Mocassin, MT	47°03'	109°57'	1310	110	384	5.7	25.2
E. Tetonia, ID	43°44'	111°07'	1864	110	401	4.2	25.9
F. Sidney, NE	41°14'	103°00'	1316	135	445	9.3	26.2
G. Denton, TX	33°12'	97°06'	192	230	845	18.5	36.2
H. Kerrville, TX	30°03'	99°09'	543	240	745	17.8	34.6

[a]Defined as the period in days between the last occurrence of 0°C temperature in spring and the first in fall.

[b]Temperature data are for Lemmon, SD, 45°56' N; 102°10' W; 791 m elev.

[c]Climatic data are from Savage, MT, 47°27'N; 104°21'W; 605 m elev.

SOURCES: Rosenberg 1982a. The climatic means were calculated for the period 1941–1970 using data listed in Climatology of the United States No. 81 (by State). Monthly normals of temperature, precipitation and heating and cooling degree days 1941–1970, National Climatic Data Center, Asheville, NC, Aug. 1973.

TABLE 5

HARD RED WINTER WHEAT PLANTING, HARVEST AND YIELD NORMALS FOR LOCATIONS IN THE NORTH AMERICAN GREAT PLAINS

Region	Nursery Location	Planting dates	Normal ripening dates	Yield ton/ha
A	Highmore, SD	8/25–9/1	8/1–8/15	2.5
B	Hettinger, ND	8/20–9/1	7/25–7/30	2.5
C	Sidney, MT	8/20–9/1	7/10–7/20	2.0
D	Mocassin, MT	8/20–9/1	8/1–8/10	2.5
E	Tetonia, ID	8/25–9/5	8/1–8/10	3.0
F	Sidney, NE	9/1–9/5	7/25–8/5	3.0
G	Denton-Dallas, TX	10/20–10/27	5/10–5/20	4.0
H	Kerrville, TX	10/15–10/25	5/5–5/15	3.0

SOURCES: Rosenberg 1982a. Data provided by Dr. V. A. Johnson, USDA/SEA/AR and University of Nebraska-Lincoln. Major source of the data is Comparison of Winter Wheat Varieties Grown in Cooperative Nursery Experiments in the Hard Red Winter Wheat Region (published annually by USDA/SEA/AR in cooperation with State Agricultural Experiment Stations).

Anthes, R. A. 1984. Enhancement of convective precipitation by mesoscale variations in vegetative covering in semiarid regions. *Journal of Climate and Applied Meteorology* 23: 541–54.

Aughey, S. 1880. *Sketches of the Physical Geography and Geology of Nebraska*. Omaha, Nebraska: Daily Republican Book and Job Office.

Bach, W. 1979. Impact of increasing atmospheric CO_2 concentration on global climate: Potential consequences and corrective measures. *Environment International* 2: 215–28.

Baldocchi, D. B., S. B. Verma and N. J. Rosenberg. 1982. Characteristics of air flow above and within soybean canopies. *Boundary-Layer Meteorology* 25: 43–54.

Baldocchi, D. B., S. B. Verma, N. J. Rosenberg, A. Garay and J. E. Specht. 1983a. Leaf pubescence effects on the mass and energy exchange between soybean canopies and the atmosphere. *Agronomy Journal* 75: 537–43.

———. 1983b. Microclimate in the soybean canopy. *Agricultural Meteorology* 28: 321–37.

Brakke, T. W., S. B. Verma and N. J. Rosenberg. 1978. Local and regional components of sensible heat advection. *Journal of Applied Meteorology* 17: 957–63.

Ehleringer, J. R. and O. Bjorkman. 1978. Pubescence and leaf spectral characteristics in a desert shrub, *Encelia farinosa*. *Oecologia* 36: 151–62.

Ellsaesser, H. W. 1984. The climatic effect of CO_2: A different view. *Atmospheric Environment* 18: 431–34.

Gausman, H. W. and R. Cardenas. 1973. Light reflectance by leaflets of pubescent, normal and glabrous soybean lines. *Agronomy Journal* 65: 837–38.

Ghorashy, S. R., J. W. Pendleton, D. B. Peters, J. S. Boyer and J. E. Beuerlein. 1971. Internal water stress and apparent photosynthesis with soybeans differing in pubescence. *Agronomy Journal* 63: 674–76.

Goetzmann, W. 1966. *Exploration and Empire*. New York: Alfred Knopf.

Grace, J. 1977. *Plant Response to Wind*. New York: Academic Press.

Greb, B. W. 1979. Reducing drought effects on croplands in the west-central Great Plains. *United States Department of Agriculture Information Bulletin Number 420*.

Hanks, R. J., L. H. Allen, Jr. and H. R. Gardner. 1971. Advection and evapotranspiration of wide-row sorghum in the central Great Plains. *Agronomy Journal* 63: 520–27.

Hubbard, K. G., N. J. Rosenberg and D. C. Nielsen. 1983. Automated weather data network for agriculture. *Journal Water Resources Planning and Management Division* 109: 213–22.

Idso, S. B. 1980. The climatological significance of a doubling of earth's atmospheric carbon dioxide concentration. *Science 207: 1462–63.*

Kellogg, W. W. and R. Schware. 1981. *Climate Change and Society: Consequences of Increasing Atmospheric Carbon Dioxide*. Boulder, Colo.: Westview Press.

Manabe, S. and R. T. Wetherald. 1980. On the distribution of climate change resulting from an increase in CO_2 content of the atmosphere. *Journal of Atmospheric Science* 37: 99–118.

Marshall, J. K. 1967. The effect of shelter on the productivity of grasslands and field crops. *Field Crop Abstracts* 20: 1–14.

Moreshet, S., G. Stanhill and M. Fuchs. 1977. Effect of increasing foliage reflectance on the CO_2 uptake and transpiration resistance of a grain sorghum crop. *Agronomy Journal* 69: 246–50.

National Academy of Sciences/National Research Council. 1976. *Climate and Food: Climatic Fluctuation and U.S. Agricultural Production*. Washington, D.C.: National Academy Press. P. 52.

National Academy of Sciences/National Research Council. 1983. *Changing Climate*. Washington D.C.: National Academy Press.

National Academy of Sciences/National Research Council-Climate Research Board. 1979. *Carbon Dioxide and Climate: A Scientific Assessment*. Washington D.C.: National Academy Press.

Neild, R. E., H. N. Richman and M. W. Seeley. 1979. Impacts of different types of temperature changes on the growing season for maize. *Agricultural Meteorology* 20: 367–74.

Newell, R. E. and T. G. Dopplick. 1979. Questions concerning the possible influence of anthropogenic CO_2 on atmospheric temperature. *Journal of Applied Meteorology* 18: 822–25.

Pelton, W. L. and A. V. Earl. 1962. The influence of field shelter belts on wind velocity and evapotranspiration. Canada, Department of Agriculture Experimental Farm Annual Report, Mimeo, Swift Current, Saskatchewan, Canada.

Rosenberg, N. J. 1969. Seasonal patterns in evapotranspiration by irrigated alfalfa in the central Great Plains. *Agronomy Journal* 61: 879–86.

———. 1977. Sown windbreaks. SPAN 20: 12–14.

Rosenberg, N. J. and S. B. Verma. 1978. Extreme evapotranspiration by irrigated alfalfa: A consequence of the 1976 midwestern drought. *Journal of Applied Meteorology* 17: 934–41.

Rosenberg, N. J. 1979. Windbreaks for reducing moisture stress. In B. J. Barfield and J. F. Gerber, ed. *Modification of the Aerial Environment of Plants*. American Society of Agricultural Engineers Monograph, pp. 394–408.

Rosenberg, N. J., ed. 1980. *Drought in the Great*

Plains: Research on Impacts and Strategies. Littleton, Colo: Water Resources Publications.

Rosenberg, N. J. 1981. The increasing CO_2 concentration in the atmosphere and its implication on agricultural productivity. I. Effects on photosynthesis, transpiration and water use efficiency. *Climatic Change* 3:265–279

Rosenberg, N. J. 1982a. The increasing CO_2 concentration in the atmosphere and its implication on agricultural productivity. II. Effects through CO_2-induced climatic change. *Climatic Change* 4: 239–54.

———. 1982b. Food and fiber in a world of increasing carbon dioxide. Response to Charles F. Cooper. In Wm. C. Clark, ed. *Carbon Dioxide Review.* 1982. Oxford: Clarendon Press. P. 324–28.

Schickedanz, P. T. 1976. *Effect of Irrigation on Precipitation in the Great Plains.* Urbana: Atmospheric Sciences Section, Illinois State Water Survey.

Seginer, I. 1969. The effect of albedo on evapotranspiration rate. *Agricultural Meteorology* 6: 5–31.

Stewart, B. A. and J. T. Musick. 1982. Conjunctive use of rainfall and irrigation in semi-arid regions. In D. Hillel, ed. *Advances in Irrigation Science, Vol. 1.* New York: Academic Press.

Sturrock, J. W. 1975. The control of wind in crop production. In L. P. Smith, ed. *Progress in Plant Biometeorology: The Effect of Weather and Climate on Plants.* Amsterdam: Swets and Zeitlinger. 349–68.

Van Eimern, J., R. Karschon, L. A. Razumova and G. W. Robertson. 1964. Windbreaks and Shelterbelts. World Meteorological Organization Technical Note no. 59.

Waggoner, P. E. 1984. Agriculture and carbon dioxide. *American Scientist* 72: 179–84.

Winter, S. R. 1981. Suitability of sugarbeets for limited irrigation in a semiarid climate. *Agronomy Journal* 72: 118–23.

Wittmuss, H. D. and A. Yazar. 1977. Conservation tillage strategies for increasing crop production with limited water. Agronomy Abstracts. American Society of Agronomy 1977 Annual Meeting.

Wooley, J. T. 1964. Water relations of soybean leaf hairs. *Agronomy Journal* 56: 569–71.

Wright, J. L. and M. E. Jensen. 1971. Peak water requirements of crops in southern Idaho. *Journal Irrigation and Drainage Division. American Society of Civil Engineers* 98: 193–201.